

HIGH ENERGY FLUXES FROM A NON-SCALING COSMIC STRING NETWORK

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Topological defects, particularly cosmic strings, can provide a mechanism to produce particles with energies of the order 10^{21} eV and higher. Here, we report on order of magnitude calculations of fluxes from a cosmic string network which evolves according to a new scenario according to which the main channel for energy loss is the particle production rather than gravitational radiation. We compare the predicted fluxes for protons (anti-protons) and neutrinos (anti-neutrinos) with observations of extremely high energy cosmic rays.

1 Introduction

Cosmic strings¹ are linear topological defects predicted to arise in many particle physics models during a symmetry breaking phase transition in the early Universe. Cosmic strings can be relevant for structure formation,² but they can also be important as a source of extremely high energy cosmic rays.³

Recently, cosmic rays events with energies above 10^{20} eV were detected by various experiments.⁴ The origin of these events is unknown to date. There are two main scenarios. The first is astrophysical and is based on the idea that charged particles are accelerated in shocks. Specifically, in the case of the extremely high energy cosmic rays, these shocks are most likely associated with active galactic nuclei (AGNs) and powerful radio galaxies. The major problems in the acceleration scenario, or ‘bottom-up’ scenario, is that in the case of AGNs the energy gained by the particle is mostly lost in collisions with the medium within which the acceleration takes place. In the case of radio galaxies this is not of much concern although the distance at which these objects are located (> 100 Mpc) constitutes a problem (see e.g. reference⁵ and refs. therein).

The other possibility is that the decay products of very massive particles produced in the early Universe are the source of the extremely high energy protons (anti-protons), gamma-rays and neutrinos (anti-neutrinos). In this scenario, also known as the ‘top-down’ scenario,⁵ no acceleration is needed since these very massive particles, which are referred to as X particles, can be as heavy as 10^{16} GeV.

In this paper, we report on an order of magnitude calculation of the fluxes of extremely high energy protons (anti-protons) and neutrinos (anti-neutrinos) in the scenario in which the particle production from a cosmic string network is maximal (VHS scenario).⁶

2 Standard Cosmic String and VHS Scenarios

In many particle physics models of matter, linear topological defects (cosmic strings) will be produced during a phase transition in the early Universe. Strings are topologically stable configurations in the core of which the superheavy Higgs and gauge particles which obtain a mass during the phase transition are trapped. Strings arise since the fields are uncorrelated in regions separated by more than the thermal correlation length ξ , which by causality at time t must be smaller than the horizon t . Strings are characterized by the mass per unit length $\mu \simeq \eta^2$, where η is the energy scale of the symmetry breaking. Right after formation, the strings are in a random tangled configuration which subsequently tends to straighten itself out. Any nongravitational string decay corresponds to the emission and subsequent decay of X particles into jets of high energy particles.

The conformal stretching due to the expansion of the Universe alone, would lead to a Universe dominated by strings. One can show, however, that the network of long strings (strings with curvature radius larger than the Hubble radius) must steadily decay and achieve a “scaling solution” in which all lengths scale with the Hubble radius and hence

$$\rho_\infty = \frac{\nu\mu}{t^2},$$

where ν is the number of strings per Hubble volume. In the standard cosmic string scenario, the decay mechanism is provided by the (predominantly gravitational) decay of cosmic strings loops formed through the intersection (self-intersection) and reconnection of long cosmic strings.¹ In contrast, according to the VHS scenario,⁶ long cosmic strings release their energy directly into X particles.

3 Particle Production

The energy conservation equation for the network of long cosmic strings is

$$\dot{\rho}_{\infty} + 2H\rho_{\infty} = -m_X \frac{dn_X}{dt}$$

where H is the Hubble parameter, and n_X and m_X are the number density and mass, respectively, of the X-particles.

The decay of the X-particles leads to the production of jets. We assume that the initial energy m_J of all jets is the same. In this case, the decay of a single X-particle will lead to m_X/m_J jets, and the number density of jets resulting from the energy release of long strings is

$$\frac{dn_J}{dt} = \frac{\nu\mu}{m_J} t^{-3}. \quad (1)$$

Because of our ignorance of the structure of the jets at extremely high initial energies, we extrapolate the QCD fragmentation function of the jets into quarks and leptons (known, at least as a good approximation, up to a few TeV). This is, of course, the source of the largest uncertainty in the calculation of the fluxes. The distribution of energies E of the primary decay products of the jet can be well approximated by a fragmentation function based on a simple $E^{1/2}$ multiplicity

$$\frac{dN'}{dx} = \frac{15}{16} x^{-3/2} (1-x)^2, \quad (2)$$

where $x = E/m_J$ is the fraction of the jet energy which the decay product receives.

The initial jet particle decays into quarks and leptons on a time scale of αm_J^{-1} , where α is coupling constant associated with the physics at an energy scale of m_J . The quarks then hadronize on a strong interaction time scale. Most of the energy (about 97%) goes into pions, the remainder into baryons. The neutral pions decay into two photons, the charged pions decay by emitting neutrinos. Note that the contribution of the primary leptons to the total flux of leptons is negligible. Integrating (2) from x to 1 with the invariant measure dx/x , we obtain the distribution of the energies of the products of two body decays of the primary particles

$$\frac{dN}{dx} = \frac{15}{16} \left[\frac{16}{3} - 2x^{1/2} - 4x^{-1/2} + \frac{2}{3}x^{-3/2} \right]. \quad (3)$$

Equation (3) applies to the spectrum of neutrinos produced in the jet, whereas equation (2) applies to the primary decay products such as protons (anti-protons). Since only about 3% of the energy of the jet goes into primary protons

(anti-protons), the distribution of these particles is given by (2) multiplied by the factor 0.03.

The expressions (1) and (2) or (3) for the number density of jets and for the energy distribution of the jet decay products can be combined to obtain the expected fractional flux $F(E)$ of high energy neutrinos and cosmic ray protons of energy E produced in the VHS cosmic string scenario. The general formula is

$$F(E) = \int_{t_c}^{t_{isd}} dt' e^{-t/t_c} \frac{dn_J}{dt'} (z(t') + 1)^{-3} \frac{dN}{dE'} (z(t') + 1), \quad (4)$$

where t_c is the earliest emission time for a particle with present energy E , and t_{isd} is the latest time that the emission from the cosmic string network can be considered to have isotropized by the present time.¹⁰ The most important propagation effects for protons (anti-protons) of extremely high energies are:^{5,8} *i*-) pair production and *ii*-) photoproduction of pions (GZK⁷ cutoff at energies above 10^{11} GeV drastically limits the distance to the source). In the case of neutrinos,^{5,9} the leading energy loss effect is the interaction with the (presently) 1.9 K cosmic neutrino background. The propagation effects determine the limits in the integral (4).

4 Diffuse fluxes

In order to calculate the diffuse flux of protons and neutrinos we have to take into account that in the VHS scenario cosmic string loops collapse almost immediately after their formation. Therefore, the X particles are produced along the string. Because the inter-string distance grows as the Universe expands, eventually this distance is bigger than the attenuation length for the propagation of the particles. For the propagation of neutrinos this effect is small because neutrinos interact only weakly and their attenuation length is comparable to the horizon. On the other hand, protons at extremely high energies have an attenuation length smaller than ~ 100 Mpc. Therefore, the flux is exponentially suppressed as the inter-string distance increases beyond this value.¹¹

Fig.(1) shows the fluxes from an order of magnitude calculation of extremely high energy protons and neutrinos originating from the decay of X particles produced by cosmic string decay in the VHS scenario. Due the fact that the inter-string distance is much bigger than the attenuation length for protons, the proton flux is suppressed. The neutrino flux is shown for various values of $G\mu$ taking $m_J = \eta$ as the initial jet energy.

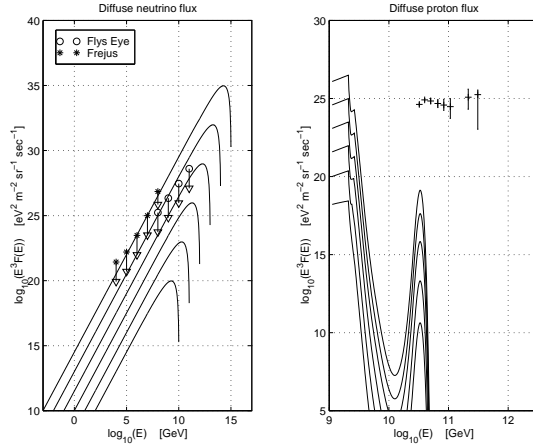


Figure 1: Diffuse neutrino flux (left) and diffuse proton flux (right) in the VHS cosmic string scenario for various values of $G\mu$ (from top to bottom, $G\mu = 10^{-6}, 10^{-8}, 10^{-10}, 10^{-12}, 10^{-14}, 10^{-16}$). Points with arrows represent upper limits on the diffuse neutrino flux from the Fréjus¹² and the Fly's Eye¹³ experiments. Points with error bars correspond to the combined cosmic ray data from the Fly's Eye and AGASA experiments.⁴

5 Conclusion

The order of magnitude calculations we have performed here show that if a cosmic string network evolves as described by the VHS scenario, the flux of extremely high cosmic rays can be used to constrain the value of $G\mu$ to $G\mu < 10^{-10}$ (see Fig. 1). The predicted flux is dominated by neutrinos, and thus if the observed events are due to strings, they cannot have a proton or anti-proton as a primary.

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